

PRIORITY SCIENCE TARGETS FOR FUTURE SAMPLE RETURN MISSIONS WITHIN THE SOLAR SYSTEM OUT TO THE YEAR 2050. F. M. McCubbin¹, J. H. Allton¹, J. J. Barnes¹, J. W. Boyce¹, A.S. Burton¹, D. S. Draper¹, C. A. Evans¹, M. D. Fries¹, J. H. Jones¹, L. P. Keller¹, S. J. Lawrence¹, S. R. Messenger¹, D. W. Ming¹, R. V. Morris¹, K. Nakamura-Messenger¹, P. B. Niles¹, K. Righter¹, J. I. Simon¹, C. J. Snead², A. Steele³, A. H. Treiman⁴, K. E. Vander Kaaden^{1,3}, R. A. Zeigler¹, M. Zolensky¹, and E. K. Stansbery¹, ¹NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058. ²Texas State University, Ingram School of Engineering, 601 University drive San Marcos, TX 78666. ³Geophysical Laboratory Carnegie Institution of Washington 5251 Broad Branch Rd. NW Washington DC 20015 ⁴Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058 francis.m.mccubbin@nasa.gov.

Introduction: The Astromaterials Acquisition and Curation Office (henceforth referred to herein as NASA Curation Office) at NASA Johnson Space Center (JSC) is responsible for curating all of NASA's extraterrestrial samples. JSC presently curates 9 different astromaterials collections: (1) Apollo samples, (2) LUNA samples, (3) Antarctic meteorites, (4) Cosmic dust particles, (5) Microparticle Impact Collection [formerly called Space Exposed Hardware], (6) Genesis solar wind, (7) Stardust comet Wild-2 particles, (8) Stardust interstellar particles, and (9) Hayabusa asteroid Itokawa particles. In addition, the next missions bringing carbonaceous asteroid samples to JSC are Hayabusa 2/ asteroid Ryugu and OSIRIS-Rex/ asteroid Bennu, in 2021 and 2023, respectively. The Hayabusa 2 samples are provided as part of an international agreement with JAXA.

The NASA Curation Office plans for the requirements of future collections in an "Advanced Curation" program. Advanced Curation is tasked with developing procedures, technology, and data sets necessary for curating new types of collections as envisioned by NASA exploration goals. Here we review the science value and sample curation needs of some potential targets for sample return missions over the next 35 years.

Mercury: Results from the MESSENGER spacecraft have shown that Mercury is an endmember among the terrestrial planets in terms of structure, chemical makeup, and density, among other physical and chemical characteristics [3]. So far there are no known samples of Mercury among the meteorite collection. Sample return from Mercury would not only provide ground truth to MESSENGER results, but it would provide new insight into the chemical and physical makeup of the most reduced terrestrial planet in the solar system. Additionally, sample return from Mercury would provide further constraints on models of the formation of the terrestrial planets in terms of proximity to the Sun, size, composition, and oxygen fugacity.

Venus: Our knowledge of the surface chemistry of Venus is limited to the observations from the Venera landers [4]. As a companion planet to Earth and Mars (and the most Earth-like of the terrestrial planets) in the habitable zone of the solar system, an understanding of how Venus evolved geologically will provide insight into the evolution of the solar system.

Samples of the Venusian atmosphere would enable us to better address the nature and evolution of the atmospheric greenhouse. The lower atmosphere is a key link between surface and interior processes and characterizing the composition is necessary to constrain the chemistry occurring between the surface and atmosphere, as well as address questions on the volcanic history of the planet. Collection and storage of planetary gas samples would pose unique challenges that will require additional technological development.

Moon: NASA's current in situ sampling of the Moon is limited to the nearside samples dominated by materials from the Procellarum KREEP Terrane, a unique geochemical province not representative of the Moon in total. The top targets for lunar sample return to address larger solar system science questions are sieved regolith samples from the ancient South Pole Aitken Basin (SPA) and from the young lunar basalt flows near Aristarchus Crater (AC). These samples would (1) dramatically constrain the crater counting curve and test the possibility of the late heavy bombardment (important for all solid bodies in the solar system), (2) provide insight into the composition and extended evolution of the lunar interior (SPA lower crustal material, SPA cryptomare, AC pyroclastics, AC basalts), and (3) inform about tertiary crustal formation on the Moon and other single-plate bodies (evolved lithologies in AC ejecta).

Mars: Mars sample return (MSR) is the highest priority of the 2013-2022 planetary science decadal survey. Key objectives for MSR are to answer the questions of whether life existed in the past or exists today, were environmental conditions ever habitable, what is the history of water, what is the history of surface modifying processes (e.g., impact, volcanic, aeolian), why did the climate change, and how did the planet evolve (accretion, differentiation, magmatic, magnetic). Another important goal of MSR is to address questions about potential hazards and resources for human exploration. A key to meeting these objectives is to collect and return a strategically selected suite of samples.

The relatively short mission turnaround time compared to the icy moons ensures that Mars is a development platform for sample return missions geared towards life detection. The return and subsequent curation of Mars samples will provide new challenges related to

planetary protection requirements given its designation as a Class V restricted Earth return body. However, these challenges are tractable given the 40 years of preparation NASA and the planetary science community have undertaken related to Mars sample return.

Phobos & Deimos: Laboratory investigation of material from Phobos and Deimos are necessary to address questions of their origin. Phobos and Deimos have been hypothesized to originate from debris ejected from a large impact on Mars or as captured asteroids [5]. Additionally, Phobos and Deimos sample return would serve as a precursor to martian sample return.

Ceres: The Dawn mission has shown Ceres to be a fascinating planetary body with cryogenic processes that have operated in the recent past [6]. Samples from Ceres would give unique insight into the distribution and transport of volatiles within the interiors and regolith of moderately-sized airless planetary bodies. Furthermore, the isotopic composition of the silicate and volatile components of Ceres would shed light on the chemical processes of differentiation and the isotopic composition of volatiles at the interface between the inner and outer solar system. Ceres may also play a role for in-situ resource utilization (ISRU) of water and other volatiles, given its strategic position within the solar system.

Ocean Worlds: Based on the requirement for water in Earth biology, the search for life elsewhere in the solar system has been geared towards objects that have liquid water now or in their past. Planetary bodies likely to have oceans include Europa, Ganymede, Callisto, and Enceladus. These locations offer our best chances of finding life beyond Earth. Analysis of samples from water oceans beyond Earth would also provide valuable insights on the origin of water in the solar system, as well as providing insights into aqueous biotic chemistry (in the event life is found) or abiotic aqueous chemistry (should the ocean worlds prove sterile).

Of these worlds, sample return from Enceladus is the most feasible because of its geyser-like activity [7], which would allow ejected material to be captured from orbit rather than requiring landing on the surface and subsequent re-launch. If landed sample return from an ocean world is feasible, Europa remains a prime target based on the existence of hydrothermal processes between a rocky inner shell and a subsurface ocean [8].

Returning samples from ocean worlds will require technological advances for collection and long-term storage of liquid or frozen samples that must be presumed to contain biology. Furthermore, these bodies present the same Planetary Protection challenges as Mars sample return given their designation as Class V restricted Earth return. Analytical advances will be needed as well, including development of a robust set of

life detection methods to unambiguously determine whether these samples contain indigenous life.

Rings of Saturn: The rings of Saturn have been an object of fascination since Galileo first peered at the rings through his telescope in 1610. The rings are composed largely of water ice with some small fraction of lithologic components, purportedly composed of interplanetary dust [9]. The origin and age of Saturn's ring system is still unknown [9-11], but most models indicate that the rings are remnants of a Moon or giant comet that was ripped apart by tidal forces [9-11]. Sample return from each of Saturn's rings would enable comparisons of isotopic ratios within the water ice and comparisons of the minor lithic components. These data would help determine the origin and age of the rings, and they would provide valuable information about the isotopic composition of water in the outer solar system.

Comets: Comets contain the best preserved remnants of the solar system starting materials and have considerable astrobiological value. Their volatile inventory represents a link between the protosolar molecular cloud and solar nebula chemistry. Moreover, comets may have contributed a major component of the Earth's volatile inventory and organic compounds. Comets appear to have remained in a deep freeze, preserving their original components from alteration by planetary processes. Comets also contain materials from the inner solar system, so comet nucleus sample return is needed both to understand how high-temperature materials and volatiles came to coexist in these primordial bodies and to characterize the original organic materials that were delivered to Earth and other bodies in the ancient past. Returned comet nucleus samples will need to be kept organically clean and protected from high temperatures. Cryogenic sample return is a priority, long term goal.

Conclusions: Future sample return missions will present new sample handling and storage challenges and will require technological advances in the areas of cold curation, extended curation of ices and volatiles, and curation of organically- and biologically-sensitive samples [1-2]. Advanced curation will continue meet the needs of the planetary science community as NASA's exploration goals evolve.

References: [1] Allen et al., (2011) *Chemie Der Erde-Geochemistry*, 71, 1-20. [2] Zeigler et al. (2017) *Planetary Science Vision 2050 Workshop*. [3] Hauck et al (2013) *JGR-Planets* 118, 1204-1220. [4] Bougher et al (1997) *Venus II*, University of Arizona Press [5] Rosenblatt (2011) *Astronomy and Astrophysics Review*, 19, 1-26 [6] Ruesch et al (2016) *Science*, 353, 1-8 [7] Waite et al (2006) *Science*, 311, 1419-1422. [8] Kargel et al (2000) *Icarus*, 148, 226-265. [9] Canup (2010) *Nature*, 468, 943-946. [10] Dones (1991) *Icarus*, 92, 194-203. [11] Charnoz et al (2009) *Icarus*, 199, 413-428.